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Comparison of Fuel Cell and Combustion Micro-CHP under Future Residential Energy Demand Scenarios

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Abstract

Energy efficiency is likely to influence the characteristics and magnitude of residential energy demand in the future. In particular, improved thermal insulation, patterns of appliance ownership, and turnover of housing stock will change the residential energy landscape. The economics of residential micro combined heat and power (micro-CHP) - a technology to provide heat and some electricity to individual residential dwellings - are generally highly dependent on the magnitude of residential energy demand. Particularly dwellings with larger and more consistent thermal consumption perform well and also achieve substantial greenhouse gas emissions savings. This creates a tension between desirable demand-side energy efficiency and supply-side energy conversion efficiency, which both serve to reduce fuel consumption and greenhouse gas emissions from the sector. This tension exists because reduction in energy demand may discourage investment in efficient supply side technology. This paper examines the changes in economic and environmental parameters that are likely to occur for three micro-CHP technologies under scenarios for future residential energy use in the United Kingdom, with a particular focus on comparison of fuel cell based systems with their combustion based system counterparts. A variety of UK residential dwelling types and associated energy demand profiles are considered in this context.

Keywords: future energy demand, residential, insulation, cogeneration, micro-CHP

Introduction

Micro combined heat and power (micro-CHP) is potentially an important contributor to residential energy provision in the future, as it may help to meet a number of energy policy objectives. Micro-CHP can be economically attractive [1] for a dwelling occupier, can reduce damaging greenhouse gas emissions associated with residential energy provision [2, 3], and may help to improve reliability and security of local and national electricity supply [4, 5]. Micro-CHP technology, which is essentially seen as a replacement for existing home heating systems, is a part of the broader decentralised generation concept, where energy demands can be met by installing electricity generators close to the point of demand and productively using their waste heat. Decentralised generation, particularly combined heat and power, could thereby help to achieve the UK government's aspiration of a 60% reduction in greenhouse gas emissions by 2050 [6]. Action to reduce greenhouse gas emissions are important considering recent reports that the cost of emissions reduction now is significantly less than the cost of associated climate change [7].

Energy efficiency also contributes to improvements in the three key areas of energy policy. The Green Paper on Energy Efficiency concluded that the EU could save at

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least 20% of its energy consumption in a cost effective manner, contributing to competitiveness, meeting the EU's Kyoto targets, and improving security of energy supply [8]. Indeed energy efficiency is often cited as the single most cost effective measure to reduce greenhouse gas emissions and improve energy security. However, demand side efficiency and supply side efficiency interact in many situations, where price changes on one side influence value on the other side. An example of this is where price reductions in heating fuel such as natural gas can result in demand side thermal energy efficiency (such as insulation) becoming less economically attractive, as it is likely to save less money and subsequently have a longer payback period. The example of this tension investigated in this paper is where residential demand side energy efficiency influences important outcomes for efficient residential-scale supply side technology. Specifically, it investigates how changes in patterns of residential energy demand influence economic and environmental outcomes for micro-CHP technology.

This article investigates this tension for three key micro-CHP technologies; fuel cell (FC) based systems, internal combustion engines (ICE), and Stirling engines. Firstly the background to this situation is discussed, including policy context and a review of the three technologies and current and predicted trends in residential energy demand. This results in a variety of different load profiles to be considered in order to capture a broad perspective of the UK micro-CHP market, including the current housing stock, the influence of refurbishment, and the potential of new housing stock. Each demand situation is compared on the basis of cost of meeting energy demand and the associated greenhouse gas emissions. A brief analysis of market potential of each micro-CHP technology is then completed in the context of the results.

Background

Demand-Side versus Supply-Side Energy Efficiency

Conceptually, the tension between demand side energy efficiency and supply side energy efficiency is the motivation for this article. In a liberalised electricity market, efficiency on both demand and supply sides are stimulated: Generators have incentive to reduce operating costs via making their power stations more efficient, and consumers have incentive to reduce electricity use and thus cost. The situation with heating fuels is similar, except it is the primary fuel that is delivered to the consumer. In this case the consumer has incentive to reduce fuel use, and Supplier has incentive to deliver the fuel with minimum losses (i.e. leakage etc).

When a residence installs micro-CHP, the situation with respect to heating fuel remains the same, but the occupier has effectively become an electricity generator as well as a consumer. They displace some electricity that would have been bought from their Supplier, and they sell some electricity back to the Supplier. The electricity displaced is typically of high value, and is an important component of cost savings if the micro-CHP is to be profitable. Furthermore, the amount of electricity displaced is roughly proportional to the amount of heat generated by the unit. Therefore, aggregate heat demand met by micro-CHP in a dwelling is related to the economic result for micro-CHP, with high thermal demand generally equating with positive results. As a result the “conventional” economic argument for efficiency on supply and demand sides appears to have been distorted.

The primary difference between the conventional and micro-CHP situations relates to which stakeholder benefits in certain situations. Where supply and demand stakeholders are different actors, their self interest should result in efficient actions. However, where one actor is responsible for supply and demand, this efficiency mechanism breaks down. The potential investor may ask: "Do I install micro-CHP or energy efficiency measures, or both?" The answer may depend on which possibility is completed first, which in turn implies a lock-in situation where purchase of one option prevents economic purchase of the other. Essentially (for example) if an occupier buys micro-CHP, they may no longer have incentive to buy insulation, resulting in a non-optimal solution in terms of overall efficiency. Certainly more complex similar situations can be imagined, but the concept that merging of supply and demand at the residential level can result in sub-optimal efficiency lock-in remains.

Policy Context

Energy policy normally revolves around three interconnected factors; economics, environmental impact, and security/reliability of supply. The relative weight these factors are given varies according to prevailing perceptions of policy makers, which in turn are influenced by considerations relevant to the discipline of political economy. In the UK energy policy debate was dominated by economic and environmental issues in 2003 [9], and then security and environmental issues in 2006 [10]. The currently predominant security debate concerns, among other factors, the existing fleet of nuclear power stations that are approaching the end of their lifetimes, and identification of a suitable replacement, whether it is new nuclear capacity or alternatives. Energy efficient decentralised generation is frequently cited as part of a resilient energy future, and has even been put forward as a potential alternative to replace of the ailing nuclear capacity [11]. Within the broad decentralised energy paradigm, which includes technologies such as wind power, industrial and district-heating combined heat and power, and measures such as electricity storage and demand side measures, is micro-CHP. Micro-CHP technologies are residential scale electricity and heat production systems based on a variety of technologies, predominantly Stirling engines, internal combustion engines, and fuel cells. Micro-CHP could form a substantial part of an overall low carbon energy system because there is a large potential market [12] and some technologies can make a significant contribution to national electricity generation capacity [4].

In the UK policy-based support for commercialisation of micropower technologies is delivered through the Microgeneration Strategy [13] and the Energy Efficiency Commitment (EEC) [14]. The Microgeneration Strategy provides grant support for residential micropower installations through the Low Carbon Buildings Programme. Technologies supported by this programme include a range of low carbon options; wind turbines, solar photovoltaics, solar thermal systems, biomass boilers, and ground source heat pumps. Micro-CHP is not specifically supported by the programme as yet, although it is listed as a technology that will be supported. Additionally, micro-CHP is a technology that UK Suppliers can use to meet their EEC targets, encouraging them to assist customers in purchasing this technology. Further financial support for micro-CHP is available through Value Added Tax (VAT) reduction, where VAT for micro-CHP is reduced to 5% from the original 17.5%, reducing the cost of capital purchase. In 2006 additional support has been given to microgeneration through the Climate Change and Sustainable Energy Act [15], which among other complimentary measures, requires Suppliers to offer terms to buyback electricity from customers with microgeneration.

The UK government is also supporting energy efficiency in the residential sector through the Energy Efficiency Commitment which (EEC) obliges Suppliers to cut the energy consumption of their customers by a total of 130TWh for the 2005-2008 commitment period [14]. Suppliers usually aim to achieve their targets by assisting homeowners to install measures such as loft and cavity wall insulation, efficient boilers, appliances and low energy lighting [16]. Another energy efficiency policy measure is the EU Directive on the Energy Performance of Buildings [8] which came into force in 2006. The implementation of this directive in the UK requires all building to have an Energy Performance Certificate when they are constructed, sold or rented. This certificate will have a format similar to that of electrical appliances, rating the building in a category from A-G.

Overall it is clear that energy policy in the UK is generally supporting both residential energy efficiency and micro-CHP. Interaction between these measures is rarely considered in any detail.

Micro Combined Heat and Power

Technologies

Micro-CHP is small scale electricity and heat generation technology, typically with electrical capacity between $1kW_e$ and $5kW_e$, at voltage and frequency appropriate for interconnection with residential electricity loads. Useful waste heat produced during electricity generation can be used for space heating or to provide domestic hot water (DHW). The primary components of a micro-CHP system are an electricity generator (various types, as discussed below), a supplementary thermal system (such as a condensing boiler), a thermal management system including heat exchangers, and a control system and/or power electronics. Most systems are designed be alternatives to a boiler or other home-heating system, and as such will be required to provide similar comfort levels, similar installation space requirements and costs to such systems.

Three candidate micro-CHP technologies are considered in this paper; fuel cell (FC) based systems, internal combustion engines (ICE), and Stirling engines. Technical characteristics, development issues, and capital costs of each of these technologies are discussed below.

FC-based micro-CHP is not yet a mainstream commercial technology, although a number of demonstration projects have yielded promising results in terms of energy consumption and greenhouse gas emissions reduction. Two key technologies are commonly associated with the stationary FC-based micro-CHP market; polymer electrolyte membrane fuel cell (PEMFC), and solid oxide fuel cell (SOFC). Examples of PEMFC and SOFC development for micro-CHP can be found in refs [17-19]. Both of these technologies are characterised by high electrical efficiency in the range of 30% to 45% LHV[3] for mature systems. Overall efficiency including useful heat recovered for space/water heating would be in the range 80-90% LHV. High temperature fuel cells, such as SOFC, may take some to time to heat up to full

[3] LHV: lower heating value

operating temperature. Lower temperature PEMFC systems should not suffer so much in this regard, although their start/stop times and electrical and overall efficiency may be impacted by the need for fuel reforming where hydrocarbon fuels are utilised. Fuel cell durability is an important area of technical research, with lifetimes often correlated with the number of start/stop cycles, and performance degradation accelerated by frequent ramping up/down of FC electrical output. Although solutions may exist to this issue, it is prudent at this stage to assume that the technology has limitations regarding the allowable number of start/stop cycles and ramping rates. The fuel cell technology modelled in this article is generic (broadly representative of PEMFC of SOFC technology) and represents medium term technology, with estimates of costs and characteristics of mature mass produced systems.

Internal combustion engine (ICE) micro-CHP technology is available commercially. In the UK the Baxi/Senertec DACHS system is a $5kW_e$ CHP generator suitable for very large residential or multi-family dwellings. This system has been reasonably successful in Europe (particularly Germany), with more than 12,000 installations. In the USA and Japan, Honda (through various partnerships) is supplying ICE-based micro-CHP in the 1.0 and $1.2kW_e$ range. In Japan a target market of 15,000 installations per year of ICE-based ECOWILL systems has been identified, with each system costing approximately £3,500 (US$7,000). ICE electrical efficiency is typically around 25% LHV, with overall efficiency around 90%. ICE technology is well understood and frequently applied, with a long history in transport and stationary energy applications.

Stirling engine micro-CHP is based on the closed-cycle piston heat engine concept developed by Robert and James Stirling around 1816. It operates via a temperature difference between the two ends of a closed cylinder with internal piston, with the working fluid cycling between hot and cold ends of the cylinder via a regenerative heat exchanger. The technology is entering the commercial market, with demonstration projects underway in the UK and elsewhere. Examples of Stirling engine micro-CHP products include WhisperGen and Microgen units. Stirling engine electrical efficiency is low at around 10%, with overall efficiency around 90%. Units can start rapidly, and may be controlled to operate at a variety of set-points.

Market Potential of Micro-CHP

Micro-CHP has significant market potential. The technology is a replacement for existing home heating systems, notably boilers. The MicroMap project reported that in Europe at between 5 million and 12.5 million dwellings could have micro-CHP installed by 2020 [20]. In the UK alone there could be 5.6 million homes with the technology by 2020 [12]. At approximately £3,000 per installation this represents considerable investment (£16.8 billion) for the UK. Assuming the units are $1kW_e$ each, total installed capacity would be 5.6GW, about 7% of current national installed capacity. Clearly micro-CHP could be an important contributor to future UK energy supply, and analysis of the economics and environmental impacts for current and future dwellings is timely in light of current development and field trials [21].

Residential Energy Efficiency

Energy efficiency in the residential sector can be boosted by a variety of measures, from simple zero-cost behavioural options through to full refurbishment of dwellings.

A list of potential measures and their estimated payback periods are presented in Table 1.

Measure	Simple Payback Period (years)
Behavioural/Awareness Measures[4]	n/a
Efficient Lighting	1-3
Efficient Appliances (A-rated)	1-3
Hot Water Cylinder Insulation	1-2
Full Package Heating Controls	4-6
A-Rated Condensing Boiler (distress purchase, compared with B-rated model)	>1
Roof/Loft Insulation	1-4
Cavity Wall Insulation	1-3
Timber Floor Insulation	3-5
Solid Floor Insulation	8- >10
Draught Proofing	6-7
Window Secondary Glazing	8- >10

Table 1: Residential Efficiency Measures and Payback Periods [22]

The payback period for many of the energy efficiency measures listed in Table 1 are short, and in most cases represent a sound investment (i.e. payback period is shorter than the lifetime of the product). Regardless of this positive image of the cost effectiveness of the measures, take-up can still be slow. Regulation to increase efficiency of available products in the residential sector has proven to be more effective in catalysing change than waiting for the market to respond to positive price signals. However, some suggest such approaches are overly prescriptive, and energy efficiency advice through dialogue is effective and less Machiavellian. Since April 2005 in the UK, regulations stipulate that all boiler installations must be condensing models, with exceptions granted in some circumstances. Minimum efficiency standards remove the least efficient products from the market, and energy efficiency labelling of equipment pushes forward the best performers.

Changes in building insulation standards over time for newly constructed dwellings can be discussed in terms of minimum U-values[5] required by building regulations. Table 2 shows the trend of these minimum standards over time in Britain. Clearly significant improvement in building standards has been achieved, and further changes in 2006 shift the focus from energy consumption to greenhouse gas emissions, with the aim of achieving a 20% reduction in energy use over a similar building constructed to the 2002 standard. The government’s 2005 pre-budget statement indicated that housing constructed post 2016 should be built to “zero carbon” standards.

[4] Behavioural/awareness measures include turning down thermostat, closing curtains to reduce thermal losses, turning off lights not in use and turning off standby appliances, and other zero cost actions taken by the dwelling occupier.

[5] U-value is a synonym for thermal transmittance, which is defined as the rate of heat transfer through 1m^2 of a material due to temperature difference of 1 degree Kelvin. U-value incorporates all modes of heat transfer; conduction, convection, and radiation.

Year	Roof U-Value (W/m^2K)	Wall U-Value (W/m^2K)	Window U-Value (W/m^2K)	Floor U-Value (W/m^2K)
1965	1.42	1.7	-	-
1976	0.6	1.0	-	-
1982	0.35	0.6	-	-
1990	0.25	0.45	-	0.45
1994	0.2	0.45	3.0	0.35
2002	0.16	0.35	2.0-2.2	0.25

Table 2: Regulated Minimum U-Values for New Buildings in Britain [23]

Changes to the building regulations do not apply to refurbished housing, a significant area of the market that must be addressed if substantial savings in the domestic sector are to be realised. Implementation of performance certificates for all housing will encourage refurbishment but does not require it. Therefore, although new housing is likely to be thermally efficient, turnover in housing stock is slow and even with accelerated construction programmes it is unlikely to have significant impact in coming decades [24]. The potential for energy efficiency in the existing housing stock, were they to be refurbished, was analysed in the 40% House report [24]. It was assumed that by 2050 refurbishment U-values would be 0.25 W/m^2K for cavity walls, 0.25 W/m^2K for solid walls (externally insulated), 0.15 W/m^2K for lofts, and 0.8 W/m^2K for glazing. This resulted in annual average of 9,000kWh space heating demand.

Trends in Residential Energy Consumption

In order to analyse future economic and environmental scenarios for micro-CHP, it is necessary to quantify prevalent trends in residential energy demand. The following two sub-sections examine recent patterns of demand, trends over the past few decades, and hypothesise regarding future developments. The information presented here is referred to in context in the *Input Data* and *Results and Discussion* sections.

Electricity Demand

In 2005 residential electricity demand in Great Britain accounted for 34% of final electricity consumption, equating to approximately 120GWh. This translates to an average consumption of 4,600kWh per household, with the lowest average consumption occurring in the North East (3,900kWh) and highest occurring in the East of England (5,100kWh) [25]. These figures include properties that utilise electric water heating. Properties on an “ordinary tariff” (as opposed to an “economy7” tariff suitable for operation of electric storage heaters) have an average annual electricity demand of around 3,900kWh [26].

Based on data from a set of dwellings in the Milton Keynes Energy Park [27], Figure 1 shows an estimate of distribution of annual electricity demand for England. This distribution was achieved by fitting a gamma distribution to the sample data. The data is clearly skewed to the right, and although the mean is approximately 3,900kWh, the median is around 3,300kWh.

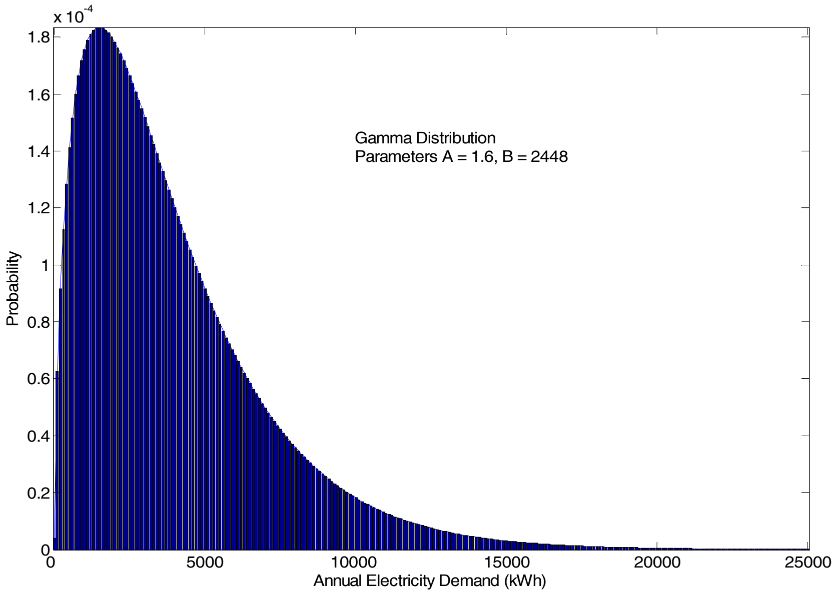

Figure 1 Estimated Probability Density Function for Annual Electricity Demand in England

Electricity demand is also particularly volatile, with significant peaks in demand occurring frequently, particularly due to use of appliances with high power ratings. The influence of these peaks in analysis of onsite generation has been investigated in Hawkes and Leach [28] and Wright and Firth [29], both of which concluded that fine temporal precision (5 to 10 minute) is required to adequately capture the characteristics of demand from an economic and environmental point of view.

Between 1970 and 2000 residential energy consumption for lighting and appliances rose 157%. Energy consumption for lighting alone increased 63% between 1970 and 2000 (11% from 1990 to 2000). Cold appliance energy use experienced particularly spectacular growth, at 274% of 1970 levels in 2000. Overall there have been significant rises in appliance ownership levels over these decades, with most dwellings now owning a fridge-freezer, VCR, Microwave, washing machine and TV. There has also been a significant increase in the levels of ownership of tumble dryers, dishwashers and DVD players [30], and a trend towards ownership of several televisions and stereos per household.

It is necessary to attempt to synthesise the information provided above to gain a picture of likely scenarios for future electricity demand at the individual dwelling level. However, there are a number of competing influences as summarised in Table 3.

Device	Possible Trend	Hypothesised Effect
Lighting	Incandescent to CFL	Reduction in night-time base load
Fridge/Freezer	Small Increase	Higher consistent cyclical base load
Tumble Dryer	Increase	Daily/Weekly peaky consumption
Dishwasher	Increase	Daily/Weekly peaky consumption
Television	Increase: Several per Household	Standby power and stable consumption when in use
VCR	Decline/Stable	Minor

DVD	Increase: Several per Household	Minor
Washing Machine	Stable	Minor
Microwave	Stable	Minor
Computer	Increase: Several per Household	Consistent cyclical consumption when in use
Stereo	Stable	Minor
Air Conditioning	Unknown	Unknown
New Devices	Unknown	Unknown

Table 3: Predicted Trend in Lighting and Appliance Ownership, and Possible Demand Profile Influence

Lighting energy consumption could remain stable or increase slightly, largely due reduced use of incandescent bulbs and a shift towards a larger quantity (in lumens per square metre) of compact fluorescent lighting (CFL). Appliance ownership is likely to continue to increase, although these items should become more efficient. When the factors in Table 3 are considered together, it seems likely that domestic electricity consumption will increase due to further rises in appliance ownership. It is possible that lighting demand will decrease, particularly if regulation removes incandescent bulbs from the market, but this decrease should be absorbed by other appliances. There appears to be no basis for assuming residential demand will become more volatile; energy efficiency improvements in some appliances may counteract increased ownership and high powered devices (e.g. 3kW kettles).

Ultimately it is difficult to definitively conclude what the combined influence of possible changes in residential electricity demand will be. It seems likely that demand will increase, but precise influence on base load and more volatile load cannot be determined. For this study electricity demand profiles from existing dwellings are assumed to be valid in scenarios modelling future situations.

Heat Demand

Residential heat demand is comprised of space heating and domestic hot water (DHW), which combined accounts for 82% of residential energy use. Demand for natural gas (the most common heating fuel in the UK) from small consumers (consuming less than 73,200 kWh/year) totalled 426GWh in Great Britain in 2004, an average of roughly 20,500kWh per dwelling. Residential natural gas demand varies from an average of 18,600kWh in the South West, to 21,000kWh in Scotland, consistent with climate differences between the north and south of the island [25].

Figure 2 shows the distribution of annual heat demand in the UK housing stock, adapted from Mariyappan [31]. Based on this figure, it is possible to conclude that only a small number of dwellings experience near the “average” gas demand, and the distribution of demands in quite broad, with a distinct tail corresponding to higher demands.

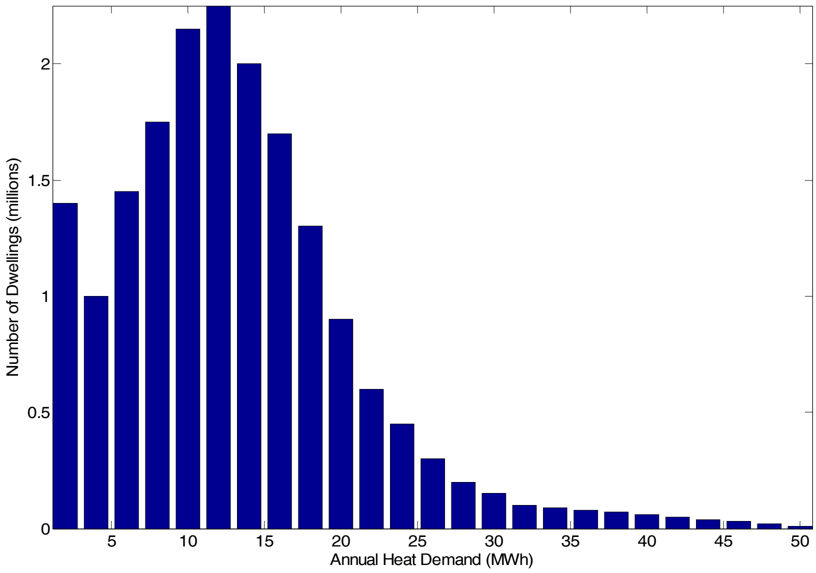

Figure 2 Distribution of Annual Heat Demand in the UK [31]

Between 1970 and 2000, national aggregate energy use for space heating and DHW increased by 24% and 15% respectively. However, energy use per household fell by 6% [30]. Indeed space heating energy demand per dwelling remained constant between 1970 and 2001 at approximately 50PJ [23]. This was due to a variety of competing influences:

- Rise in the number of dwellings.
- Insulation improvements.
- Increase in ownership of central heating.
- General rise in temperature inside dwellings by 6.25ºC between 1970 and 2001.

Improvements in energy efficiency through insulation and efficiency of heating systems where effectively cancelled out by the general rise in temperature in dwellings, resulting in constant average heat load. According to the BREHOMES model the average temperature in dwellings in 2001 was 18.89ºC [23]. If it is assumed that dwelling occupiers will continue to demand higher temperatures until the average reaches between 19ºC and 21ºC, it follows that further insulation improvements after these maximum temperatures have been reached will result in reduction in average thermal energy consumption per dwelling.

In 2004 approximately 37% of dwellings in Great Britain that could potentially install cavity wall insulation have done so [32]. Loft insulation has achieved higher penetration with 60% of properties benefiting from 100mm or more. Privately rented dwellings are less likely to be well insulated [32]. Approximately 30% of all properties had less than 100mm of loft insulation, and the majority of the remaining 10% did not have a loft, usually due to stacked construction where loft insulation would be less important in terms of heat loss [33]. Ownership of double-glazing on windows reached almost 84% in 2004 (around 43% having double-glazing on more than 80% of windows) [32]. Building Regulations changes in 2002 require all new windows to be double-glazed, so uptake of this measure will be strong in the future. Based on this information assumptions can be made about potential U-values for the elements of refurbished housing and U-values for new housing can be taken from the relevant building regulations (see Table 4).

Domestic hot water (DHW) load in Great Britain in 2001 was 409PJ, corresponding to approximately 5,100kWh per dwelling [23]. DHW consumption, in litres per day, is linked to the number of occupants in a dwelling. Typical consumption is between 100 litres per day for single occupancy to 300 litres per day for family homes. Trends in energy consumption for DHW are therefore related to changing patterns of occupancy in addition to ownership/insulation of storage tank and pipe system. In 1970 average annual DHW load was 6,200kWh. Mean household size decreased from 2.9 to 2.3 persons per household between 2001 and 1970, and ownership of hot water tank insulation rose from approximately 75% to 95% over this period. Since the mid-1980's tank-based DHW systems are increasingly being replaced by instant hot water systems, particularly combination boilers. This trend should further reduce DHW energy consumption, avoiding inevitable losses associated with DHW storage tanks [23]. With respect to micro-CHP, it is likely that the ideal system will have an associated DHW storage tank, providing potentially valuable decoupling of heat demand and heat supply. Therefore it is expected that DHW loads for micro-CHP systems would be higher than those for combi boilers systems.[6]

Overall there is a clear trend towards higher efficiency for space heating and DHW, and a demand for higher internal temperatures. Refurbishment of housing can still result in substantial energy savings, particularly with regard to cavity wall insulation and increasing depth of loft insulation. New housing should be significantly more efficiency than the average existing or refurbished property, because new dwellings must be fully insulated. Building standards are expected to become even stricter in this regard over the next decade, perhaps resulting in average annual heat demand of dwellings as low as 2000kWh by 2050. This study takes onboard this information, and endeavours to model space and DHW demand for existing housing stock, estimates for refurbished dwellings, and new stock built to the 2002 standards. These assumptions, and corresponding heat loss coefficients and resulting annual space heating demand are shown in Table 4. Table 4 presents space heating demand for two possible internal temperatures; 20ºC and 25ºC. This is for information purposes only, given the possibility that in the future higher internal temperatures will be desired. The analysis results presented in this article refer only to the 20ºC case.

[6] Uncertainty remains regarding whether or not micro-CHP would be used to meet DHW loads. The ability to meet DHW loads improves the economics of the technology.

	Terraced House	Semi-Detached House	Detached House	Bungalow	Flat
Number of Properties (thousands) in 2001	6,766	6,936	3,956	2,051	4,639
Existing Dwellings					
Heat Loss (W/ºC) [23]	243	276	365	229	182
Space Heating Demand with 20ºC Internal Winter Temperature (kWh)	14,600	16,600	22,000	13,800	11,000
Space Heating Demand with 25ºC Internal Winter Temperature (kWh)	19,900	22,600	30,000	18,800	15,000
Refurbished Dwellings					
Heat Loss (W/ºC)	176	199	311	147	117
Space Heating Demand with 20ºC Internal Winter Temperature (kWh)	10,600	12,000	18,700	8,900	7,000
Space Heating Demand with 25ºC Internal Winter Temperature (kWh)	14,400	16,300	25,500	12,000	9,600
New Dwellings					
Heat Loss (W/ºC)	107	121	189	88	70
Space Heating Demand with 20ºC Internal Winter Temperature (kWh)	6,400	7,300	11,300	5,300	4,200
Space Heating Demand with 25ºC Internal Winter Temperature (kWh)	8,800	9,900	15,500	7,200	5,700

Table 4: Space Heating Demand for by Dwelling Type for Current Stock, Refurbished Stock, and New Stock in Great Britain [23, 33][7]

[7] Heat loss coefficients for refurbished and new dwellings based on assumed U-values. Refurbished dwellings U-values: Roof = 0.35W/m^{2o}C, Floor = 0.45W/m^{2o}C, Walls = 0.6W/m^{2o}C, Windows = 3.0W/m^{2o}C. New dwellings U-values: Roof = 0.16W/m^{2o}C, Floor = 0.25W/m^{2o}C, Walls = 0.35W/m^{2o}C, Windows = 2.1W/m^{2o}C (approx 2002 Building Regulations).

Input Data and Analysis Method

The analysis method applied in this study relies on a number of assumptions and approximations in order to make the problem tractable. Analysis is completed for five dwelling types; terraced, semi-detached, detached, bungalow and flats. Three thermal insulation categories are investigated; existing average dwellings, an estimate of refurbished dwellings, and new dwellings built to the 2002 building regulation standards. In addition to the thermal insulation categories, three electricity demand categories are chosen, equating with small, average[8], and large electricity demand, based on demand profiles derived from the DTI Domestic Photovoltaic Field Trial. The three electricity demand profiles are linked with dwelling types on an intuitive basis.

Thermal demand for each dwelling type and insulation case are based on data presented in Table 4 for the case of 20ºC internal temperature. DHW demands are based on a median 200 litre/day demand of 4,000kWh per year (note this is intended as median demand, rather than mean demand). Larger (300 litre) and smaller (100 litre) DHW demands correspond with 6,000kWh and 2,000kWh consumption respectively. Annual electricity demands are approximately 1,200kWh for “small”, 3,000kWh for “average”, and 8,000kWh for “large”. All profiles, thermal and electrical, are at 5-minute precision.

Technical characteristics and capital costs[9] of the three micro-CHP technologies are presented in Table 5. The “Baseline Case” represents the conventional system with which micro-CHP competes, where dwelling occupier buys electricity from a Supplier (i.e. delivered via the grid), and burns natural gas in a condensing boiler to provide heat. In this case the boiler installation cost is relatively high, corresponding with a premium guaranteed installation and high quality equipment. The fuel cell based micro-CHP represents mid-term technology transplanted in today’s market; it has higher efficiency, lower cost, and longer lifetime than existing demonstration products. However, it is a reasonable representation of developers’ expectations for the technology. ICE and Stirling engine technology representations are modelled on systems currently available commercially. All micro-CHP systems are 1.0kWe, and have a supplementary thermal system (condensing boiler) to meet peak thermal demand.

[8] Note that the “average” electricity demand profile used in this stuffy roughly correlates with the median residential demand for the UK, as indicated in Figure 1.

[9] Capital costs presented here are author’s own estimates based on perceived installed cost of mature technology. As a great deal of uncertainty surrounds these figures, results presented can be adjusted for capital cost by subtracting “System Annualised Capital and Maintenance Cost” from EAC results, and adding back new estimates.

Technology	Supplementary Thermal System Efficiency (LHV)	CHP Full Load Electrical Efficiency (LHV)	CHP Overall Efficiency (LHV)	System Installed Cost (£)	System Lifetime (years)	System Annual Maintenance Cost (£/year)	System Annualised Capital and Maintenance Cost at 12% Discount Rate (£/year)
Baseline Case (Grid/25kW$_{th}$ Boiler)	90%	-	-	£2,750	10	£100	£587
1kW$_e$ Fuel Cell Micro-CHP System	90%	40%	90%	£3,350	10	£125	£718
1kW$_e$ ICE Micro-CHP System	90%	25%	90%	£3,200	10	£125	£691
1kW$_e$ Stirling Engine Micro-CHP System	90%	15%	90%	£3,200	10	£125	£691

Table 5: Technical Characteristics of Competing Residential Energy Provision Systems

Electricity and fuel costs are as per DTI Quarterly Energy Prices in March 2007 [34]. These prices are; electricity 8.2p/kWh, gas 2.28p/kWh for consumption in 2005. It is assumed that any electricity sold back to the grid receives compensation at a rate of 4.0p/kWh, an approximation of the weighted average wholesale price of electricity.

The discount rate applied to capital investment in micro-CHP or Boiler is 12% which is a typical commercial rate (i.e. the situation modelled is where an investor such as an Energy Service Company purchases and installs the equipment, rather than the dwelling occupier), and emissions rates for grid electricity are 0.43kg CO_2/kWh, and 0.19kg CO_2/kWh for consumption of natural gas.

For each dwelling type, insulation, DHW, and electricity demand profile combination, each of the four systems described in Table 5 are applied. The equivalent annual cost (EAC) and associated carbon dioxide emissions related to meeting the energy demand are calculated using the CODEGen model (for details of approach and assumptions applied in this model readers are referred to [35]). Equivalent annual cost is the combination of annualised capital cost (presented in Table 5), maintenance cost, plus the cost of fuel and electricity consumed in the dwelling and by the micro-CHP unit, minus the revenue gained from selling electricity back to the Supplier. EAC is essentially equivalent to Net Present Value, except it can be applied to compare projects with different lifetimes.

Results and Discussion

Table 6 presents the equivalent annual cost (EAC) and emissions for each dwelling type, insulation, DHW, electricity profile combination, for each of the four systems described in Table 5. This article is concerned with the comparison of efficiency measures and micro-CHP, and comparison between various micro-CHP technologies and the baseline condensing boiler. The following two paragraphs interpret the results in Table 6 with respect to these issues.

If a dwelling owner/occupier were concerned with choosing to install micro-CHP, insulation, or both, the results presented in Table 6 can be used as a guide. For example, if the investor for an average existing terraced dwelling installed insulation measures to refurbish that dwelling (to the standard specified in Table 4), they would save £103 per year on energy bills. Therefore the maximum annualised capital cost they should pay for this is £103 per year. Alternatively, if they installed ICE micro-CHP, they would save £23 per year (this includes the annualised capital cost presented in Table 5). If they refurbished the dwelling *and* installed ICE micro-CHP, equivalent annual cost changes from £1,293 to £1,180, implying that they could spend up to £113 per year annualised capital cost on the insulation refurbishment. Therefore, in this case the insulation and micro-CHP could both be installed with a positive economic result, but they are not complimentary (i.e. the saving for doing both - £113 per year – is less than the addition of both measures independently - £103 + £23 = £126). Conversely, if the investor were considering an average existing flat, it is apparent that refurbishment saves £81 per year, but none of the micro-CHP technologies offer a positive case for investment. However, in general Table 6 indicates that installation of micro-CHP and insulation refurbishment of the existing housing stock can both be achieved with a positive economic result. Exceptions occur for Stirling engine micro-CHP for an average terraced house and bungalow cases, and all micro-CHP technologies for the average flat. Overall the cost savings apparent from insulation refurbishment are in the range of £80 to £120 per year, which in most cases would present a good case for investment in loft and cavity wall insulation. The investment case for micro-CHP is also good with a few notable exceptions. This result is consistent with conventional thinking that substantial potential for improvement exists with regard to increased insulation in the housing stock, and that micro-CHP has significant (but still limited to dwellings requiring more heat/electricity) market potential.

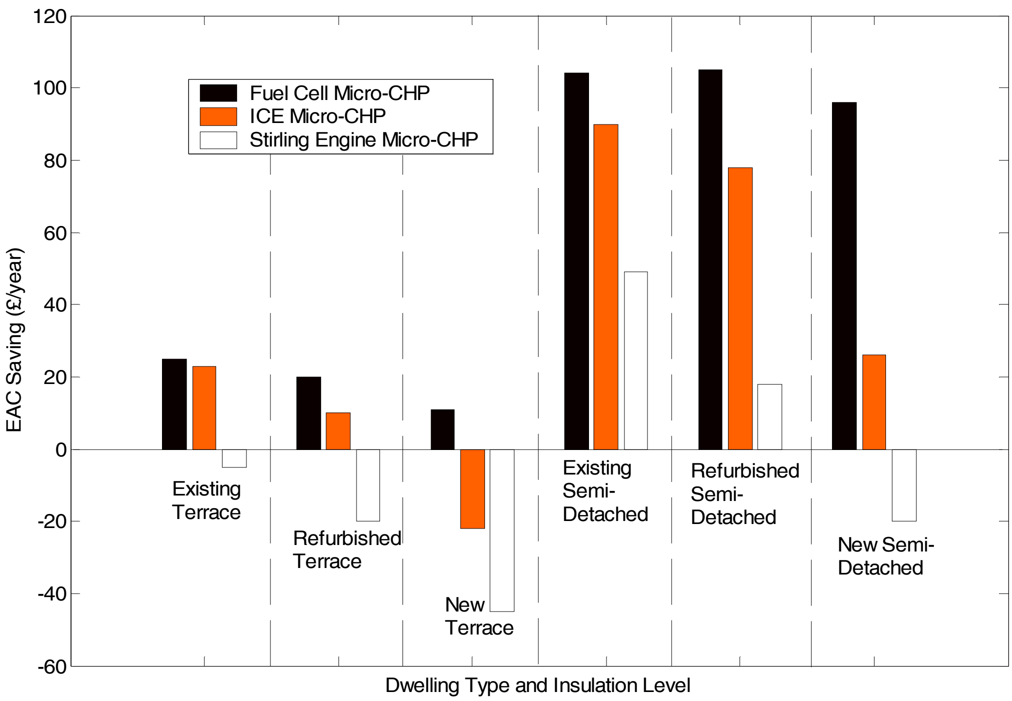

Figure 3: Equivalent Annual Cost (EAC) Savings versus Baseline (Grid/Boiler) for Three Micro-CHP Technologies for Terrace and Semi-Detached Dwellings

When comparing between micro-CHP technologies and the grid/boiler baseline case, it is apparent that the more insulated the dwelling, the less convincing is the case for investment in micro-CHP. To clarify this point two dwelling types are taken as an example; terraced and semi-detached dwellings. Figure 3 displays the equivalent annual cost (EAC) saving versus the grid/boiler baseline case for these two dwellings and the three insulation cases. In both dwelling types the EAC saving reduces with increasing insulation. In some cases the investment case becomes negative (i.e. the grid electricity and boiler option becomes more economical than the micro-CHP option). These figures provide a starting point for analysis of the future potential of micro-CHP in the UK; with the underlying message that as building regulations and other policy instruments result in dwellings with lower thermal demand, the economic case for micro-CHP is reduced, but significant market still exists.

Insulation Case	Dwelling Type	DHW Demand (litres/day)	Electricity Demand	Baseline EAC (£/year)	Fuel Cell EAC (£/year)	ICE EAC (£/year)	Stirling Engine EAC (£/year)	Baseline Emissions (kg CO_2/year)	Fuel Cell Emissions (kg CO_2/year)	ICE Emissions (kg CO_2/year)	Stirling Engine Emissions (kg CO_2/year)
Existing	Terraced	200	Average	1,293	1,268	1,270	*1,298*	5,250	4,260	4,350	4,660
Existing	Semi-Detached	300	Large	1,860	1,756	1,770	1,811	8,480	7,430	7,500	7,770
Existing	Detached	300	Large	1,984	1,878	1,887	1,916	9,580	8,480	8,490	8,700
Existing	Bungalow	200	Average	1,268	1,244	1,247	*1,277*	5,050	4,040	4,160	4,490
Existing	Flat	100	Small	978	*1,010*	*1,000*	*1,027*	3,210	2,300	2,440	2,830
Refurbished	Terraced	200	Average	1,190	1,170	1,180	*1,210*	4,390	3,450	3,600	3,990
Refurbished	Semi-Detached	300	Large	1,746	1,641	1,668	1,728	7,490	6,470	6,580	7,000
Refurbished	Detached	300	Large	1,897	1,787	1,806	1,843	8,830	7,720	7,790	8,030
Refurbished	Bungalow	200	Average	1,154	1,137	1,150	*1,185*	4,060	3,140	3,330	3,700
Refurbished	Flat	100	Small	897	*928*	*939*	*956*	2,510	1,590	2,000	2,240
New	Terraced	200	Average	1,088	1,077	*1,110*	*1,133*	3,510	2,640	3,082	3,270
New	Semi-Detached	300	Large	1,626	1,530	1,600	*1,646*	6,470	5,530	5,960	6,170
New	Detached	300	Large	1,723	1,620	1,650	1,712	7,320	6,300	6,410	6,850
New	Bungalow	200	Average	1,052	1,049	*1,090*	*1,104*	3,210	2,440	2,880	3,010
New	Flat	100	Small	815	*867*	*878*	*887*	1,800	1,160	1,550	1,660

Table 6: Key Results – Equivalent Annual Costs (EAC) and Greenhouse Gas Emissions for Meeting Residential Electricity and Heat Demand with Three Micro-CHP Technologies versus a Grid/Boiler Baseline (EAC includes both capital and operating expenditure). EAC figures in *italics* indicate a negative case for investment in that micro-CHP technology

Comparison of carbon dioxide emissions savings from insulation measures and micro-CHP is also a focus of this study. For the average existing dwelling the result here is consistent with other studies [2, 3]; micro-CHP can reduce the "carbon footprint" of residential energy provision by between 600 and 1000kg CO_2 per year. This roughly equates to between 10% and 20% of current carbon dioxide emissions from the residential sector, and is therefore a significant improvement. Table 6 can also be used to evaluate the carbon dioxide emissions reduction associated with improved insulation. The refurbishment insulation described provides approximately the same emissions reduction as installing micro-CHP; between 700 and 1000kg CO_2 per year.

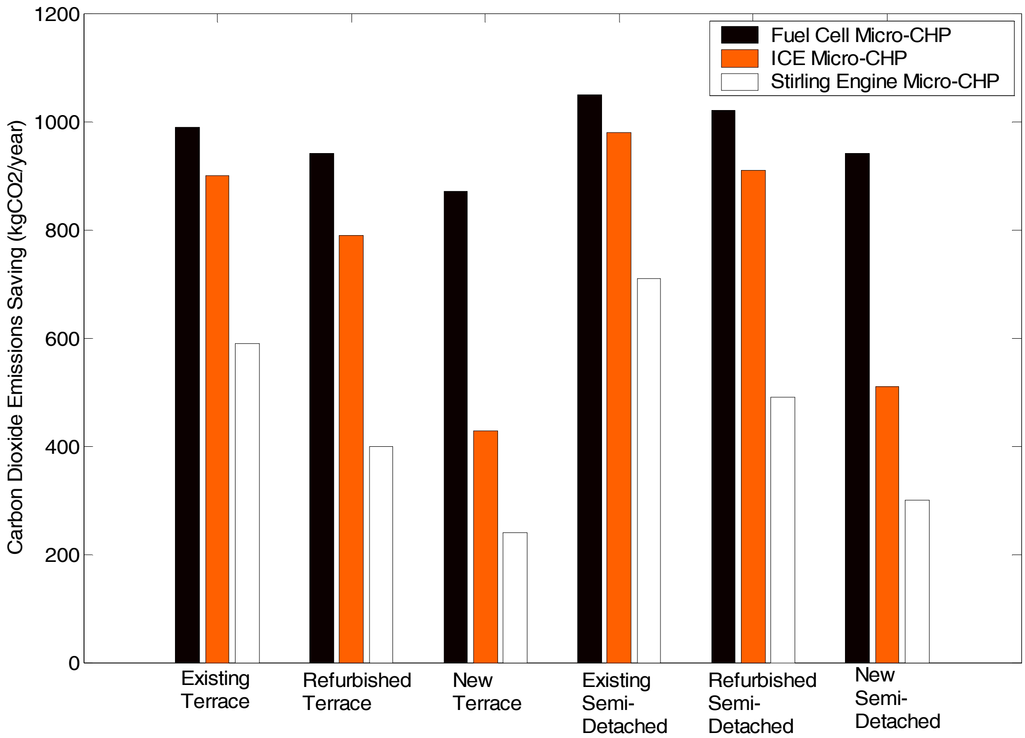

Figure 4: Carbon Dioxide Emissions Savings versus Baseline (Grid/Boiler) for Three Micro-CHP Technologies for Terrace and Semi-Detached Dwellings

In order to examine the influence of insulation levels on CO_2 emissions result between micro-CHP system types, the results for terraced and semi-detached dwellings are presented in Figure 4. The first point that can be drawn from this figure is that all technologies provide an emissions reduction. Secondly, it is clear that there if a difference between the three technologies; fuel cell micro-CHP results in the largest emissions reduction, followed by ICE micro-CHP, and then Stirling engine micro-CHP. This result correlates with the heat to power ratio of the three technologies. A low heat to power ratio implies more electricity is produced for a given heat production, and as such more grid electricity is displaced by the efficient micro-CHP, resulting in a larger CO_2 saving. The third and final point to be drawn from Figure 4 is the impact on emissions saving as insulation improves. Fuel cell based micro-CHP performs well, with emissions reduction of near 1000kg CO_2 per year regardless of the insulation level. At the other end of the spectrum Stirling engine micro-CHP emissions reduction is substantially reduced as insulation improves. Once again this result correlates with the heat to power ratio of the technologies; the low heat to power ratio technologies continue to perform well as insulation improves because they can continue to operate when heat demand is low. High heat to power ratio technologies must modulate or switch off when there is lower heat load, resulting in less impressive emissions reduction.

Overall the results presented here can be used in conjunction with the residential energy demand information presented earlier in the article to produce estimates of the market potential for micro-CHP in the UK. Although a detailed market potential study involves more factors than economics and carbon dioxide emissions and is beyond the scope of this study, a basic appraisal is presented here. Figure 1 and Figure 2 provide information regarding the distribution of annual domestic electricity and thermal consumption respectively. If one were to take the view that micro-CHP would be economically justified based a minimum annual thermal and electrical demand, it is possible to combine the distribution of demand information and minimum demand requirements to arrive at rough estimates of current market potential. Table 7 presents the author's estimates of these numbers based on results in the present study, although these estimates should be treated with caution until a complete market assessment can be completed.

Technology	Minimum Residential Annual Thermal Demand (kWh/year)	Minimum Residential Annual Electricity Demand (kWh/year)	Indicative market potential (% of total market)
Fuel Cell Micro-CHP	10,400	2,500	75%
ICE Micro-CHP	13,300	3,100	50%
Stirling Engine Micro-CHP	17,300	5,000	25%

Table 7: Authors' Estimates of Minimum Annual Thermal and Electrical Consumption in an Individual Dwelling in Order for Micro-CHP to be Cost Effective, and Related Estimate of Micro-CHP Market Potential in Great Britain

Clearly the potential market for micro-CHP is large under current the consumption and price scenario. For example, if 80% of dwellings are suitable for micro-CHP, the cost-effective market for fuel cell technology in Great Britain is of the order of 14 million installations. Using a similar approach, the market for Stirling engine micro-CHP is of the order of 5 million installations for existing dwellings.

The future market potential is more difficult to predict without detailed study, but results of this study can be used to conclude that in general the fuel cell micro-CHP technology characterised in this study should be applicable in all refurbished and new dwellings with the exception of flats. ICE-based micro-CHP should be cost-effective in a similar range of dwellings, with the exception of medium-demand terraced and bungalow new dwellings. Stirling engine micro-CHP faces the greatest challenges as insulation improves, and would be cost-effective in dwellings with larger thermal and electrical demands such as detached residences housing (for example) a family or several adults.

Conclusion

This article has developed a picture of current residential electricity and heat demand in UK dwellings, considered how building regulations and other policy instruments will influence this demand in the future, and analysed how three micro combined heat and power (micro-CHP) technologies will perform under the developed scenarios for changing patterns of demand. It is clear that as building standards are tightened and policy instruments take effect, improved insulation will result in lower thermal consumption. However this influence is partially offset by dwelling occupiers demanding higher temperatures. Trends in electricity demand are less clear, although a general increase in the number of appliances owned, partially offset by higher efficiency of these appliances, will probably result in slightly higher or constant electricity consumption. These trends in consumption were used to inform the study on the economics and greenhouse gas emissions of micro-CHP in the future.

Fuel cell, internal combustion engine (ICE), and Stirling engine micro-CHP systems were modelled and compared with the baseline case were residential energy needs are met with grid electricity and burning natural gas in a condensing boiler. It was found that in most cases some form of micro-CHP presents a positive case for investment, even when existing housing stock is refurbished. Exceptions to this result occur for flats, which usually did not have enough energy demand to justify micro-CHP investment, and for some other cases where Stirling engine micro-CHP was applied and insufficient thermal demand exists to justify this investment in existing and refurbished terraced and bungalow dwelling types. For new dwellings low heat to power ratio fuel cell technology performed well, being cost-effective in all dwelling types except flats. As heat to power ratio of technology increases, the number of dwelling types that present cost effective investment reduces, being limited to those with larger demand (e.g. detached and semi-detached dwellings).

In terms of carbon dioxide emissions, the results offer strong parallels with the economic result. All technologies achieve emissions reduction, but there is clear differentiation amongst them according to their technical characteristics. Low heat to power ratio technologies achieve highest emissions reduction (compared with the grid/boiler baseline). Additionally, as insulation improves, low heat to power ratio technology maintains a high level of emissions reduction, whilst low heat to power ratio technology is more challenged in this regard.

Finally a brief estimate of current market potential for micro-CHP was synthesised from the results. It was shown that low heat to power ratio technologies may have the largest cost-effective market in Britain of around 14 million installations, and high heat to power ratio technology may have a current market of around 5 million installations (if there were no competition between the two). These results are highly dependent on the capital cost assumptions made in this study, which are estimates of mature mass produced technology. As residential energy demand changes the market share for low heat to power ratio technologies remains constant, whilst the market share for high heat to power ratio technologies reduces.

Overall this analysis is consistent with previous studies in that it shows a significant market potential for micro-CHP. It takes this result a few steps further indicating that a substantial market remains even as building standards demand lower residential energy consumption, and that substantial carbon dioxide emissions reduction could be achieved if even a small percentage of the available market is captured. Further questions remain regarding scenarios further into the future (i.e. beyond the next two decades) when new dwellings may have even further reduced thermal demand if zero-carbon housing is achieved. However, for the short to medium term, this analysis has shown the relative merits of the three micro-CHP technologies, demonstrating that an economic and environmental case often exists for investment as patterns of residential energy demand change.

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